

SHM Design for Space Vehicles

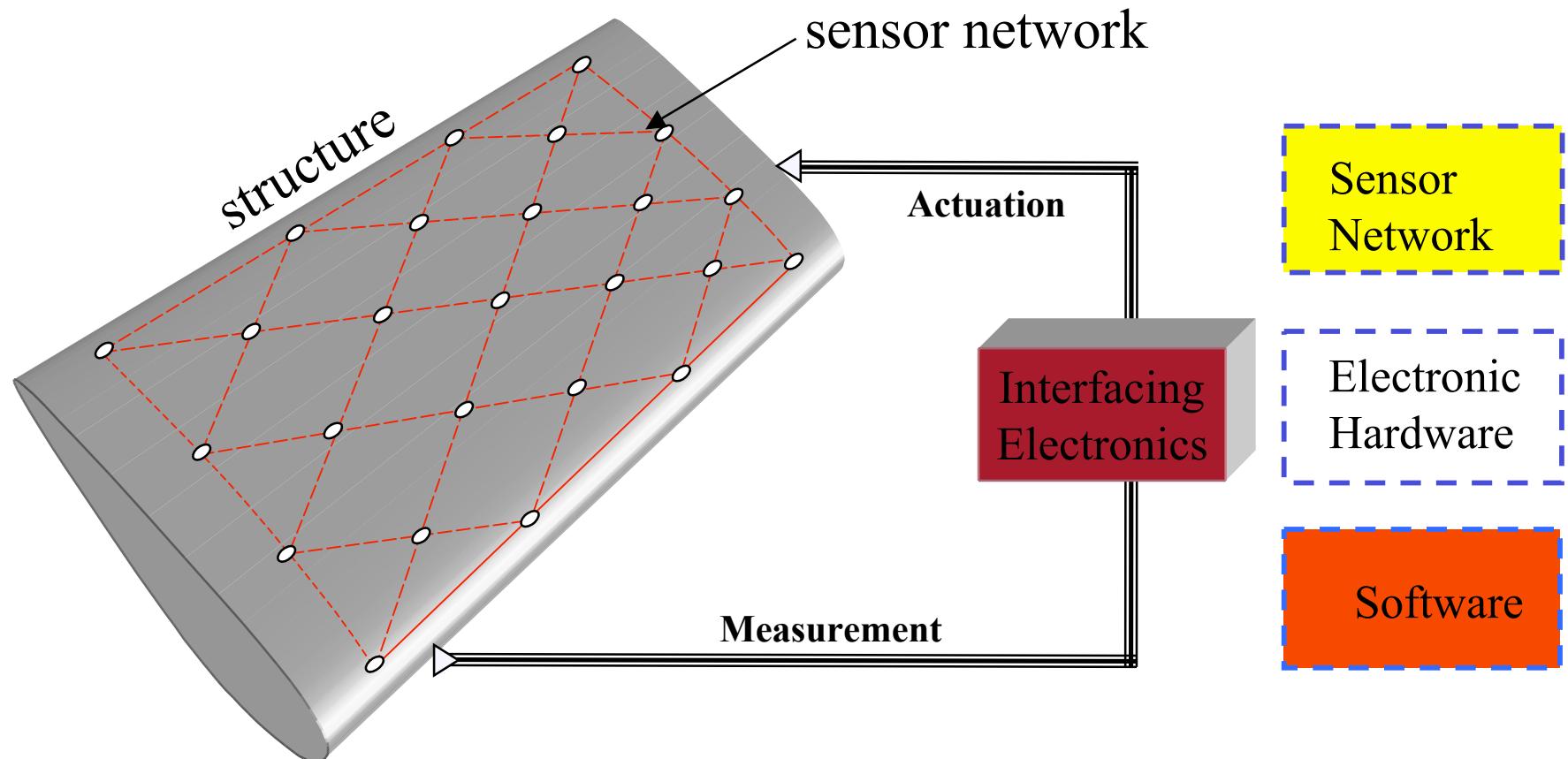
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Reliability, Safety, Performance



Structural Health Monitoring



PROBLEM STATEMENT

**GIVEN SENSOR MEASUREMENTS, DETERMINE
EXTERNAL AND/OR INTERNAL PARAMETERS.**

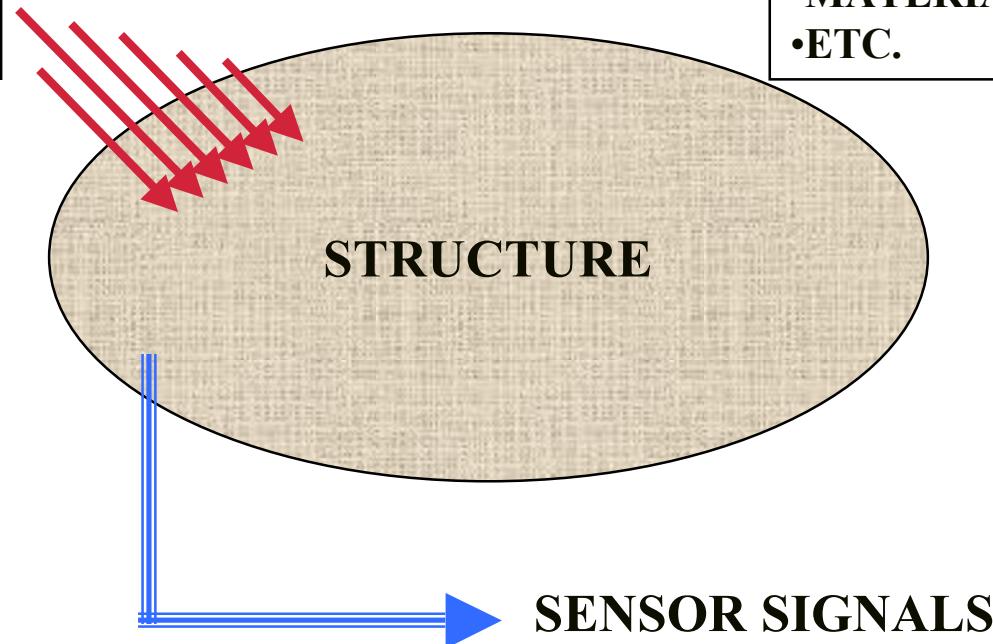
(NONLINEAR INVERSE AND NON-UNIQUENESS)

EXTERNAL:

- LOAD
- TEMPERATURE
- MOISTURE
- ETC.

INTERNAL:

- DAMAGE LOCATION
- DAMAGE SIZE/TYPE
- MATERIAL PROPERTIES
- ETC.



Results of SHM Trade Study by Boeing

Identified Top 5
High Payoff Areas

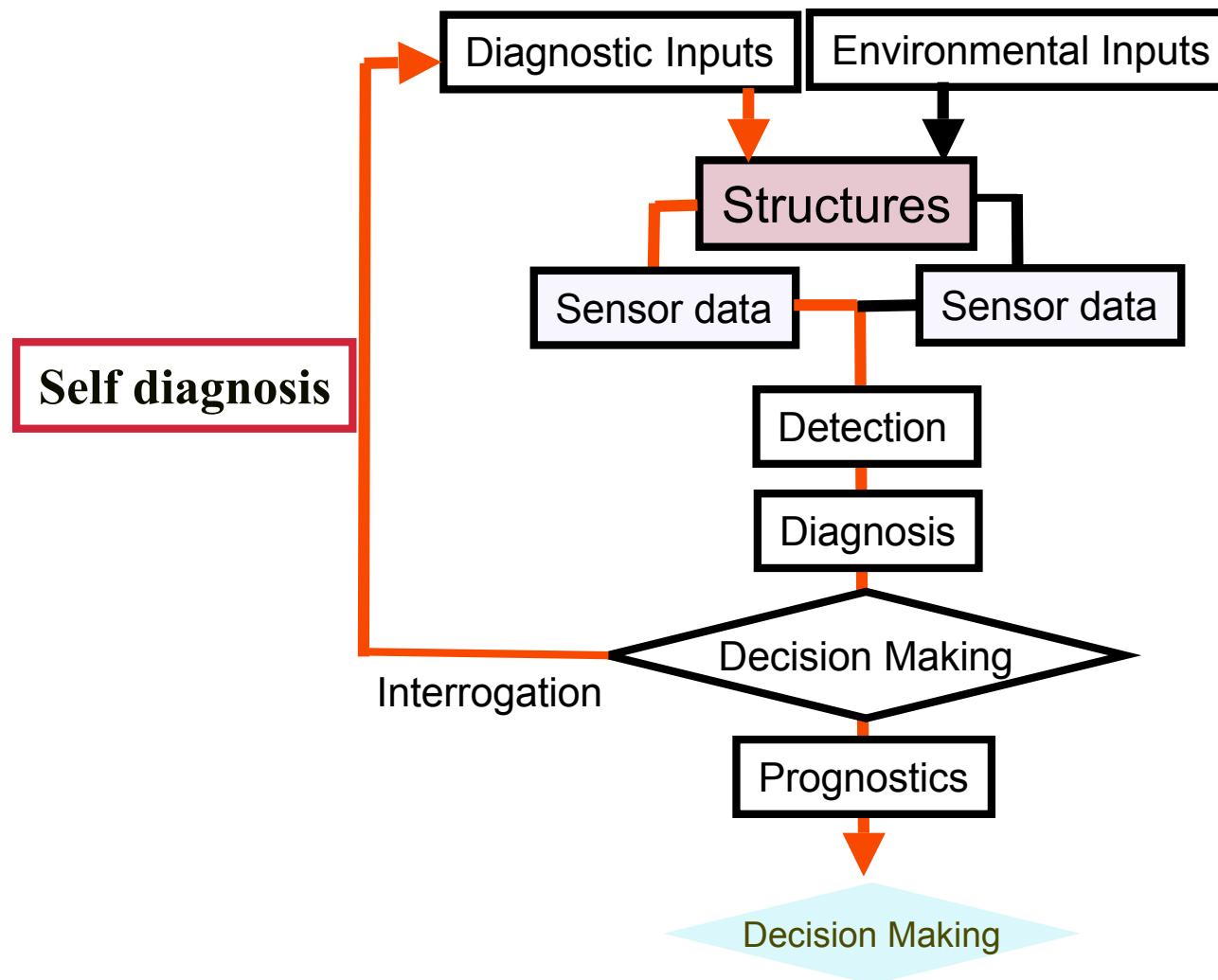
Rankings by Area	
Area	Rank
TPS	1
Tank	2
Wing Structures	3
Leading Edges	4
Thrust Structure	5

Identified Top 10
Damage/Data Types

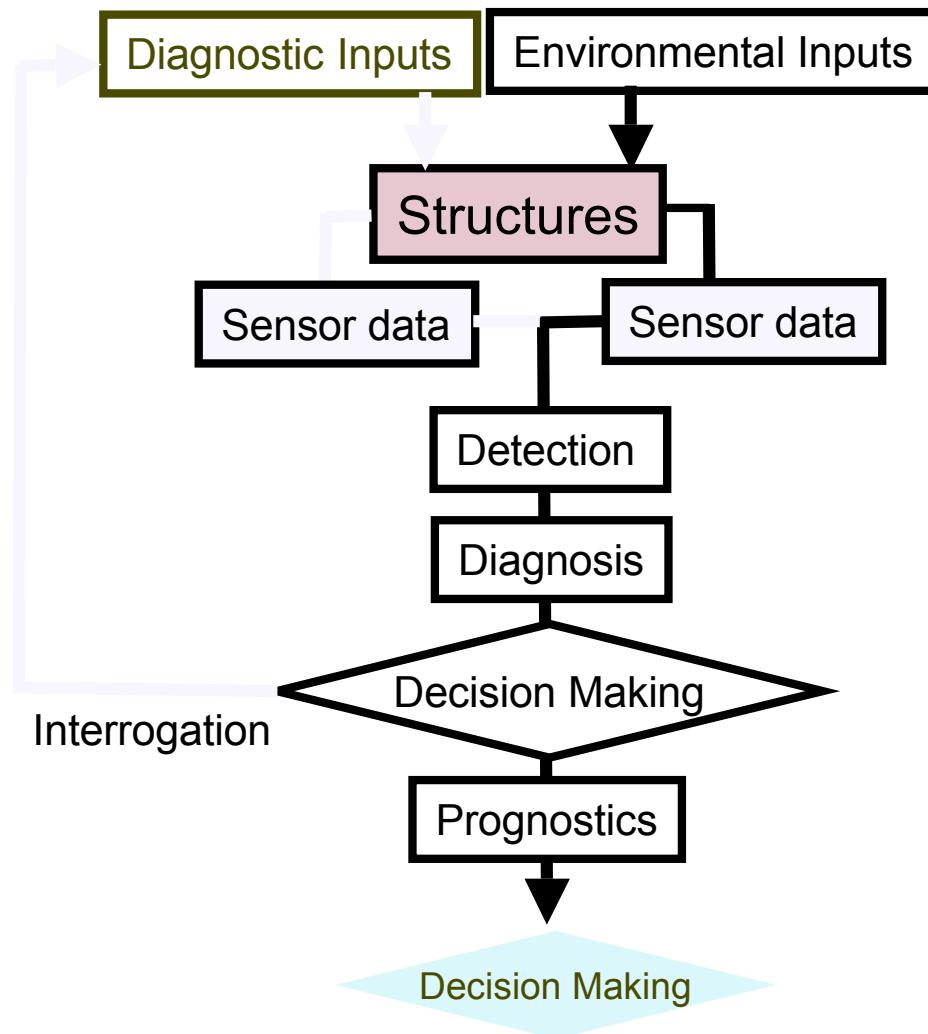
Rankings by Damage/Data Types	
Damage/Data Types	Rank
Crack growth	1
Fuel Leak	2
Over Temperature	3
Impact Damage	4
Bondline Failure	5
Composite Delamination	6
Load Monitoring	7
Temperature Monitorin	8
Leading Edge Mass Loss	9
Corrosion	10

Note: the ranking shown in the tables may vary depending on the engineering judgment, but basically with the range.

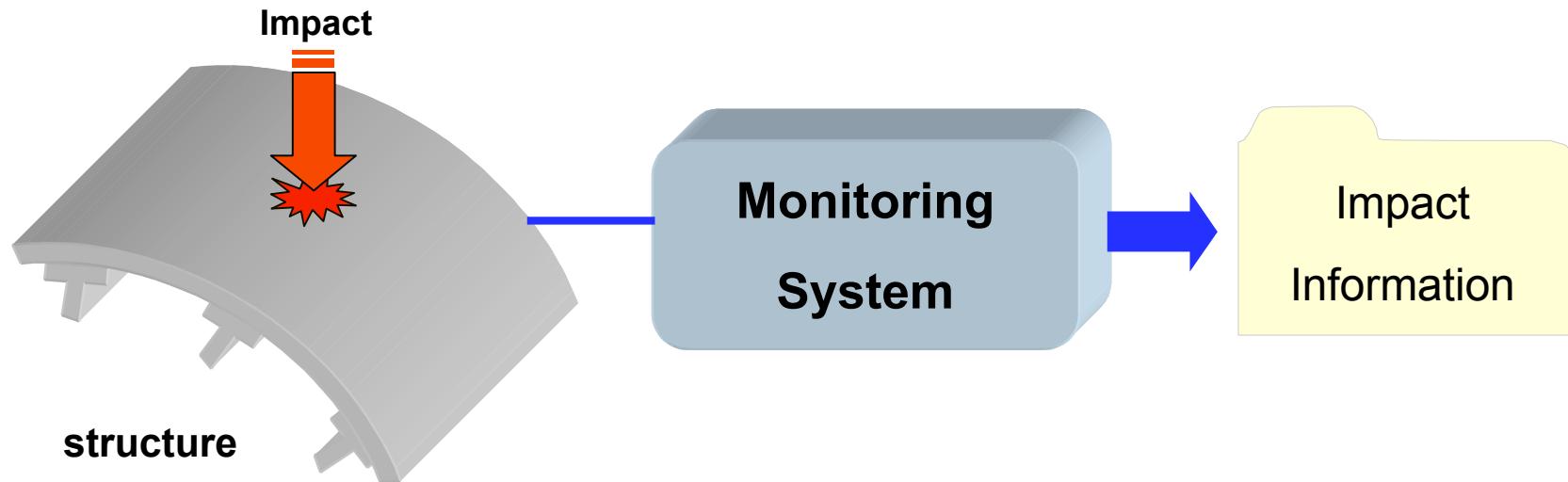
SHM System



Passive SHM System



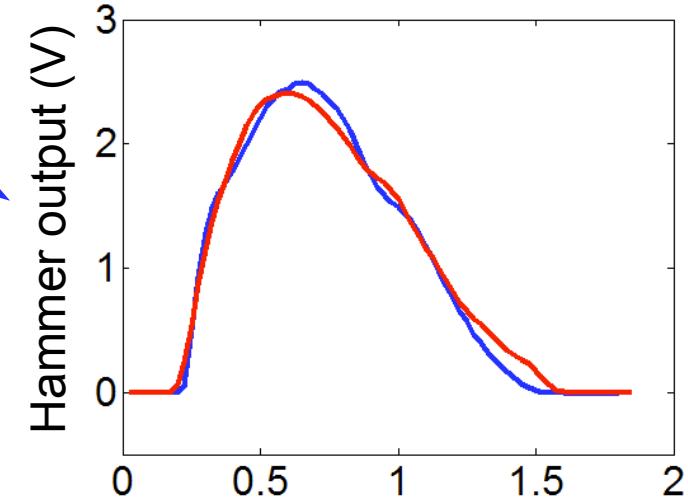
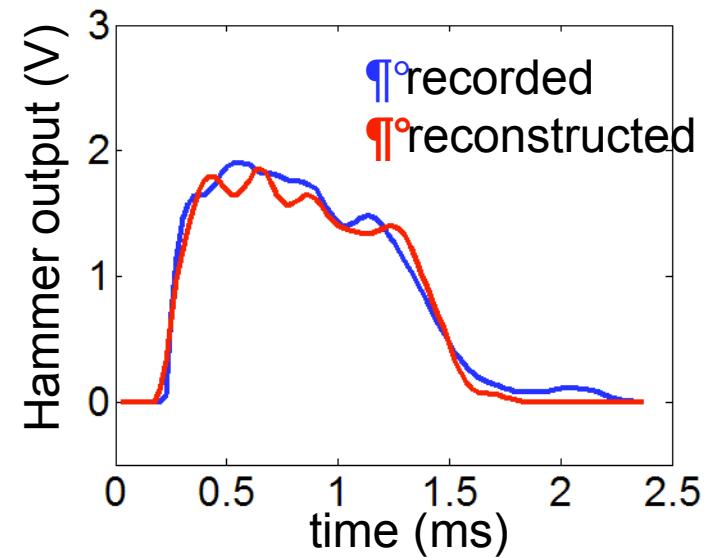
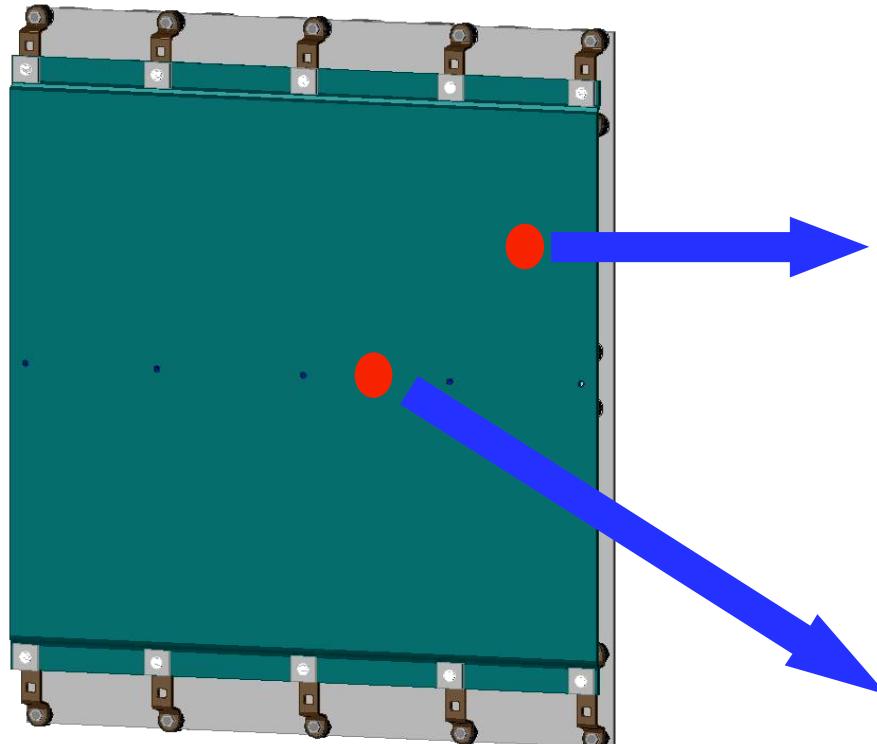
Impact Monitoring System



Impact Monitoring System

- detects impacts automatically
- makes inspection more efficient
 - localize inspection area
 - inspections could be scheduled only when necessary

Result – Force Reconstruction (TPS)

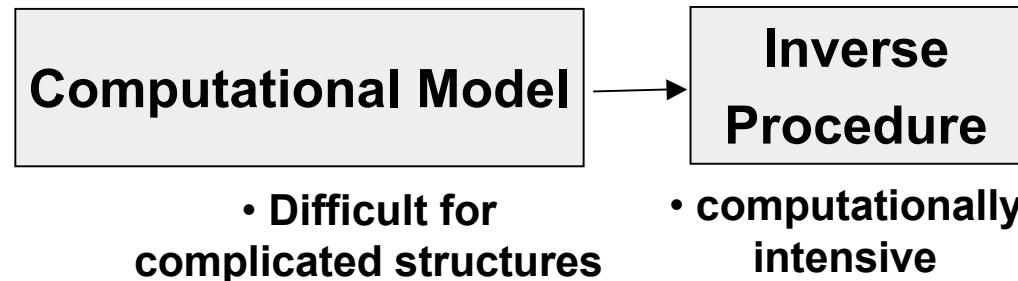


Does Size Matter ?



Impact Identification Methods

Model Based
Technique



Neural
Network

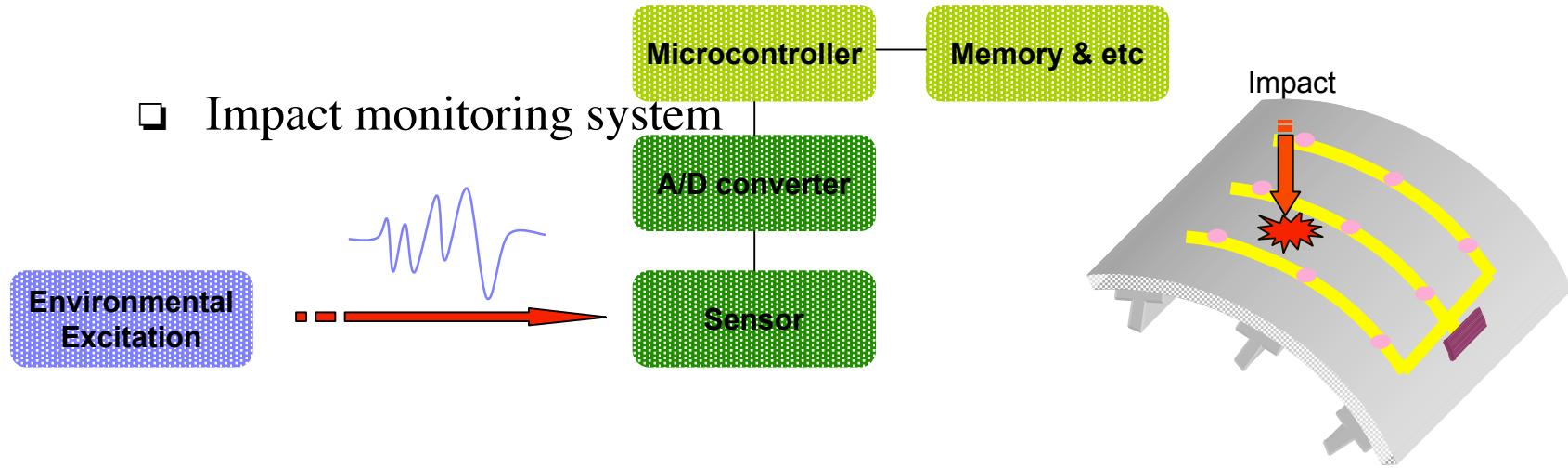


New
Approach



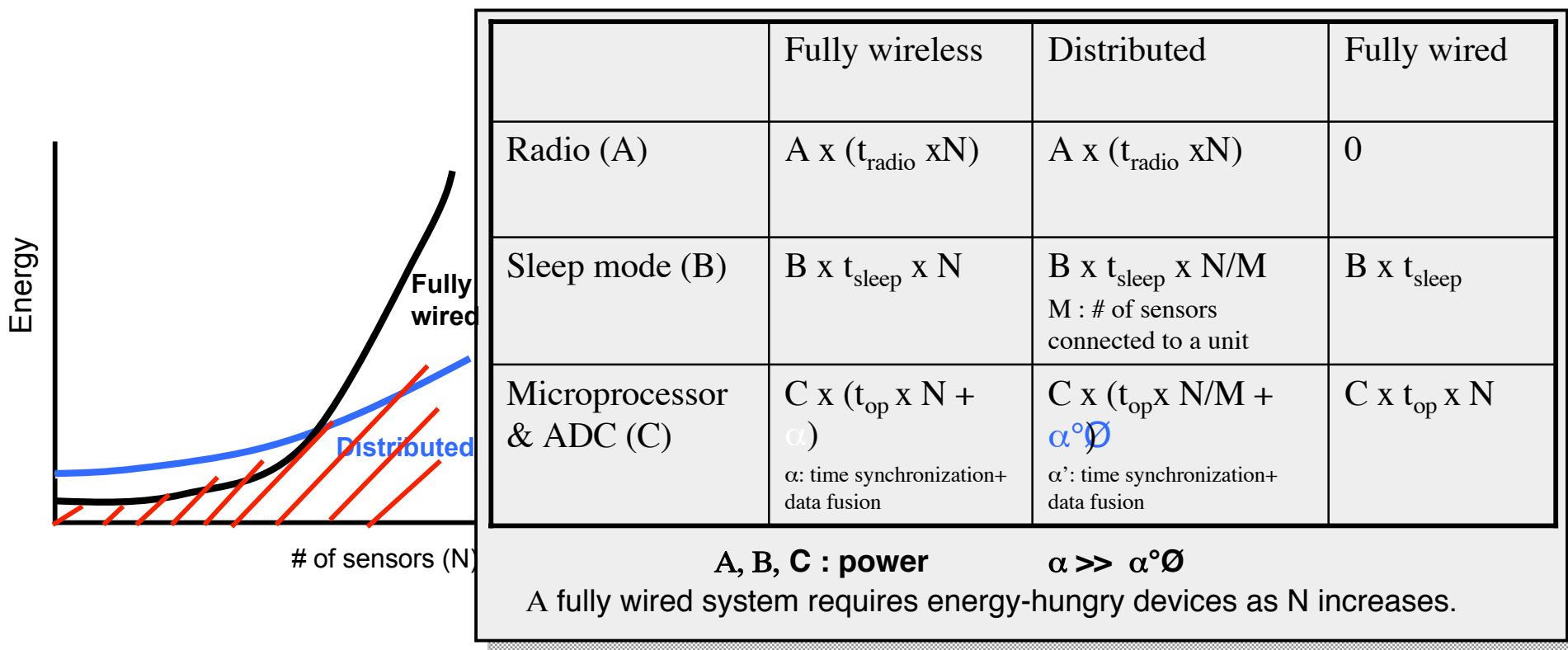
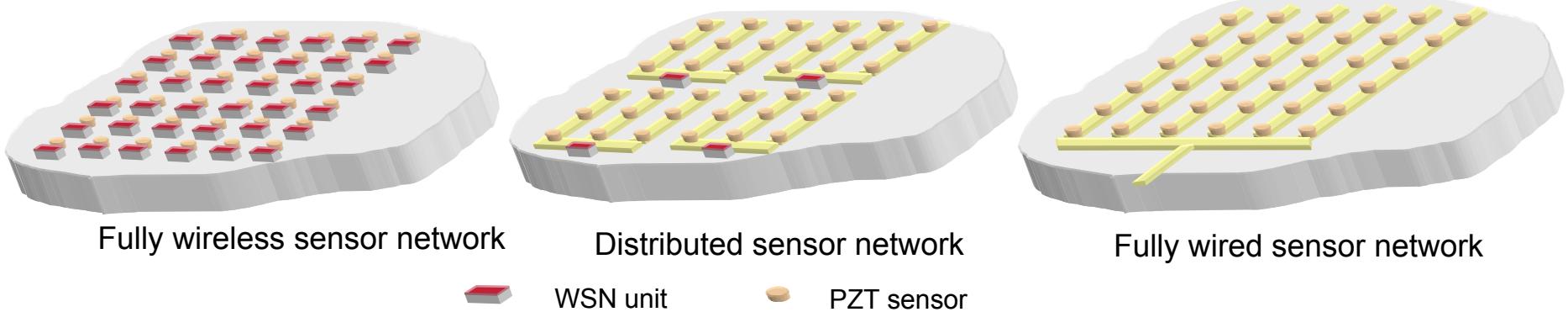
Components of Impact Monitoring Systems

□ Impact monitoring system

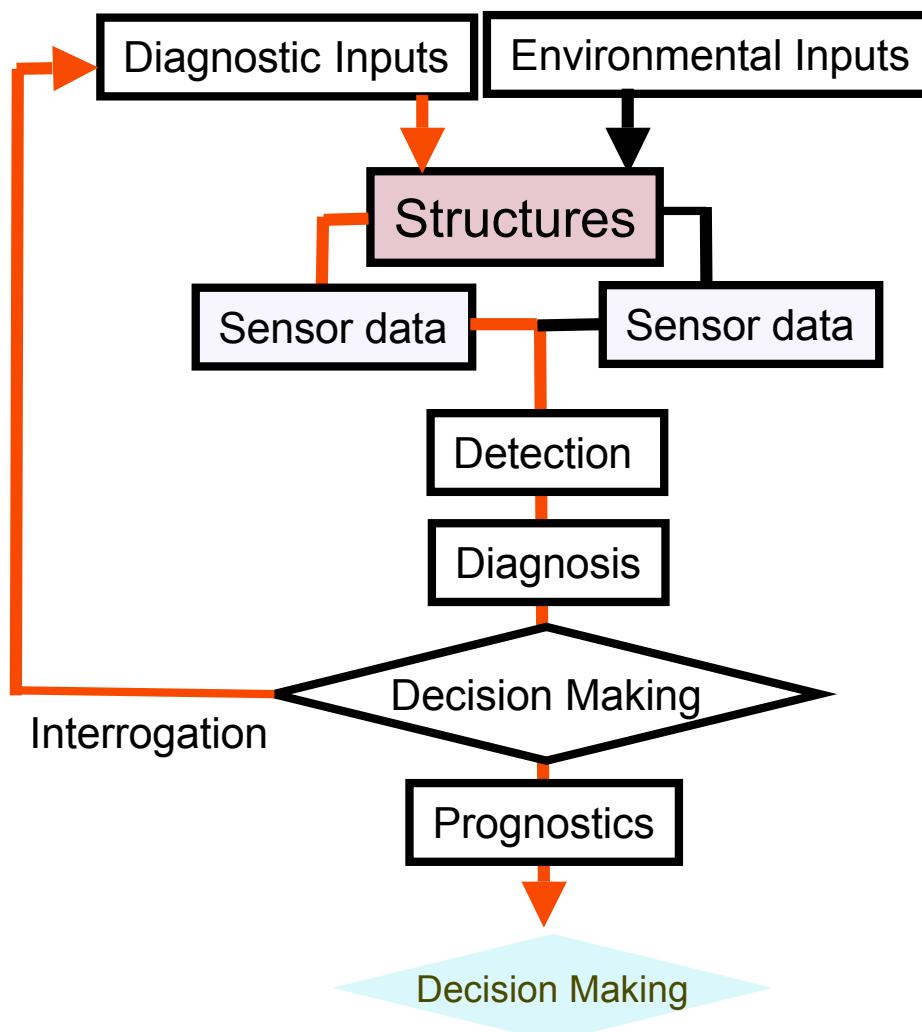


	Power consumption (mW)	Comments
sensors	0~7.5	0 for PZT 7.5 for ADXL
Microcontroller, memory, etc	0.01~2.16	MSP430 F1611 0.01 for sleep mode 2.16 for max. opr. mode
ADC	2.5~7.5	MSP430 F1611
Radio	63 ~ 71	CC2420 250kbps 0 dBm

Wireless Sensor Network Deployment of SHM Systems in Aerospace Applications



Active SHM System



Types of TPS

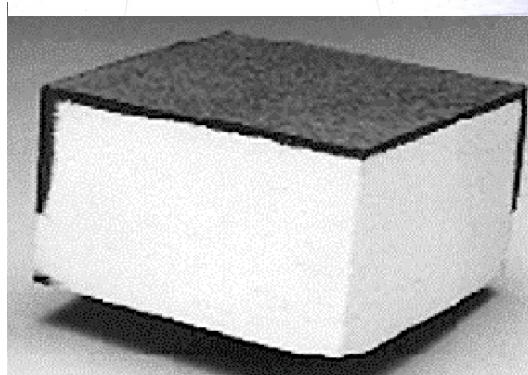
TPS panels :

Mechanically fastened joints

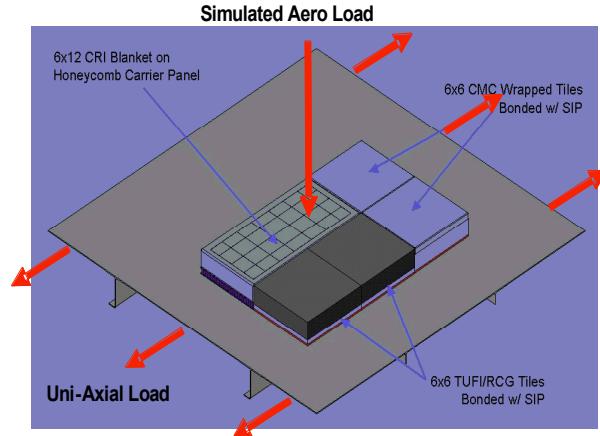


TPS tiles :

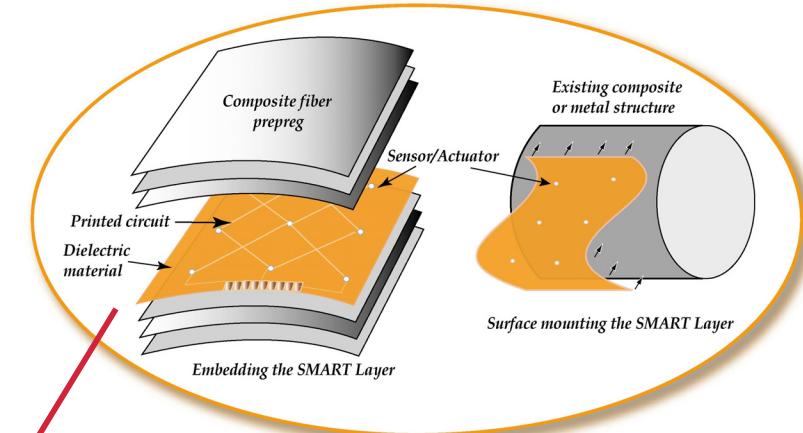
Adhesively bonded joints



Bonded TPS with Built-in Sensors



Front view



SMART layer

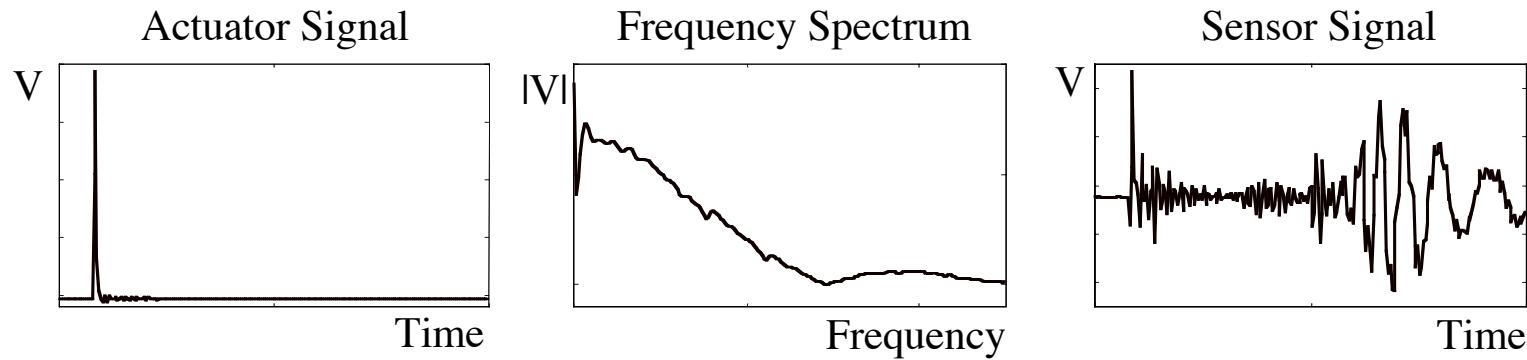


Back view

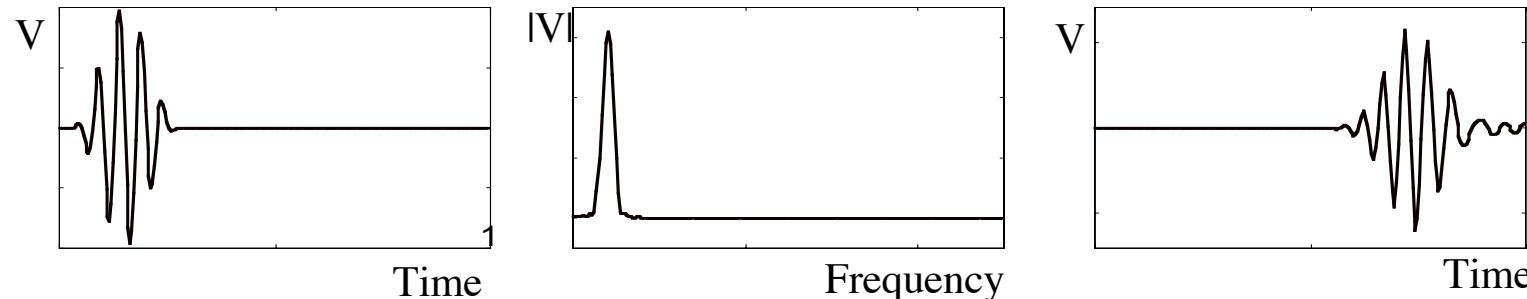
Generation of Diagnostic Signal

- Wave dispersion in plate causes distortion of waveform.
- Narrow-band signal preserves waveform.

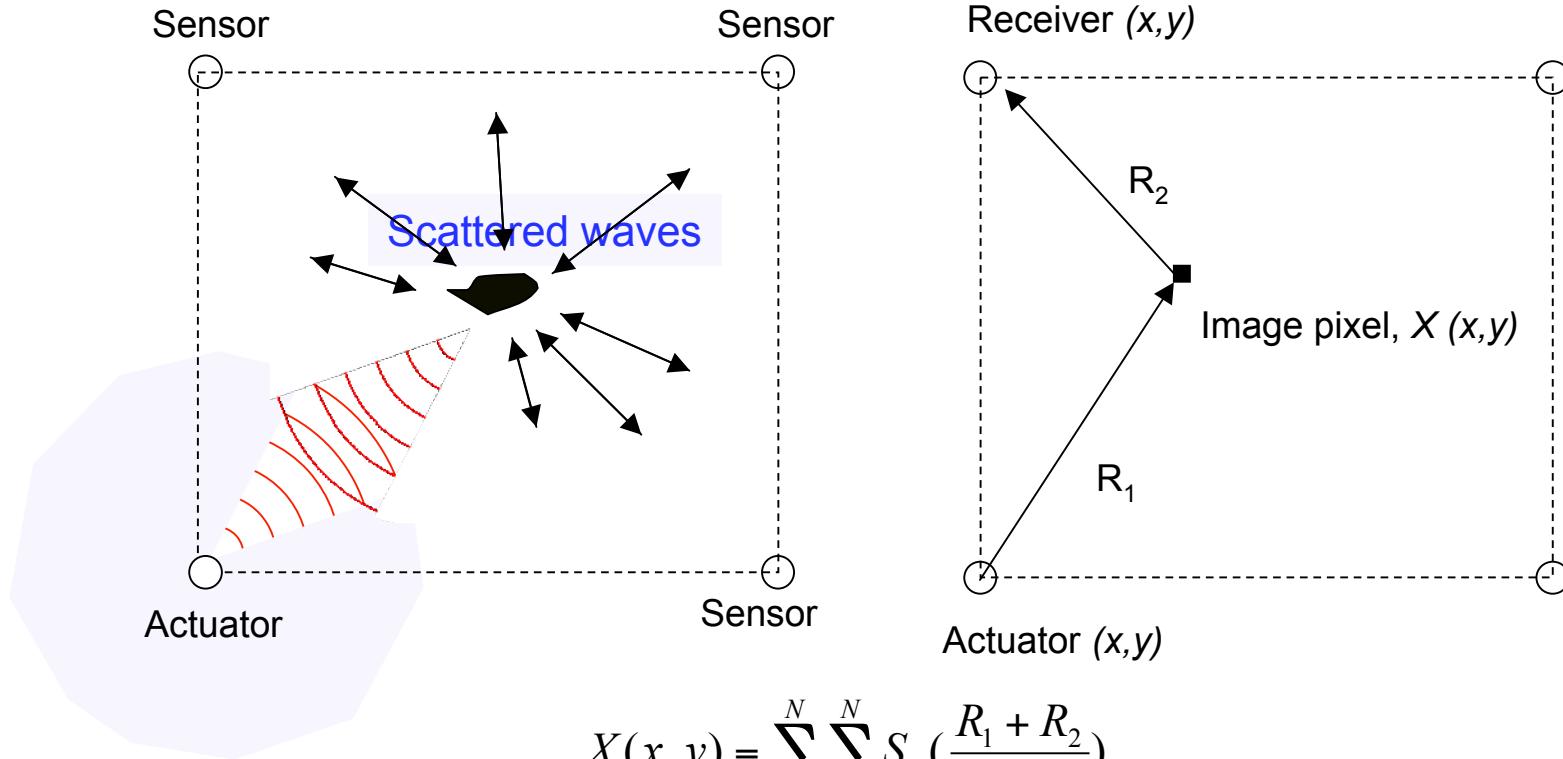
Wide-band signal



Narrow-band signal



Imaging Technique with Active Sensors



$$X(x,y) = \sum_{i=1}^N \sum_{j=1}^N S_{ij} \left(\frac{R_1 + R_2}{C_g} \right)$$

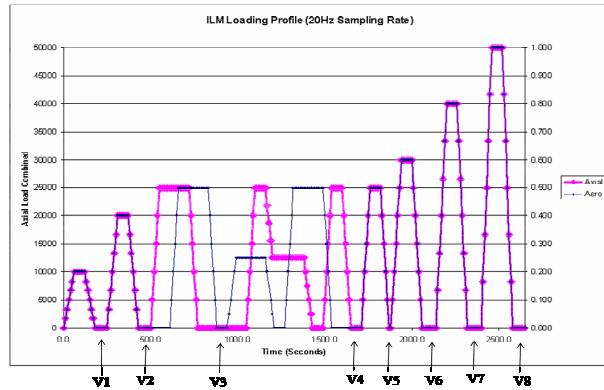
S_{ij} : Scattered signal received at receiver j by excitation of actuator i

$R=R_1+R_2$: Total time-of-flight

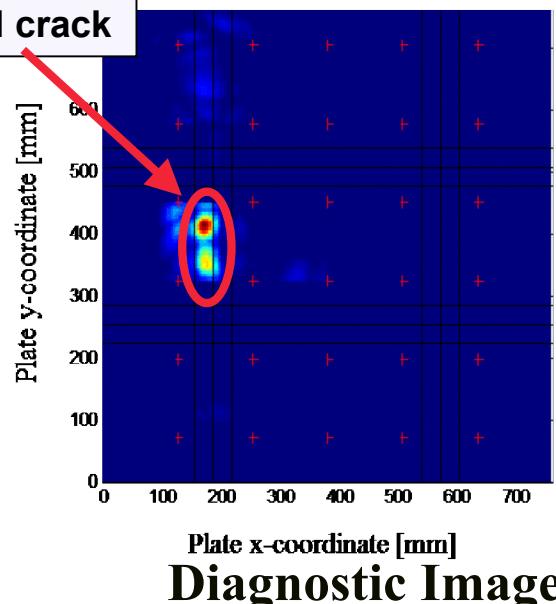
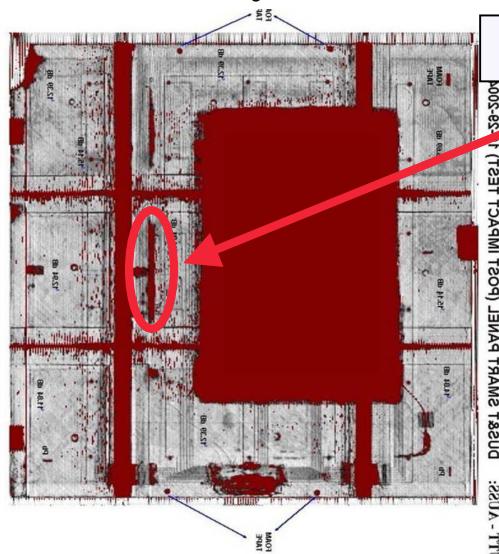
C_g : Group velocity

→ Requires only group velocity information

Bonded TPS with Built-In SHM

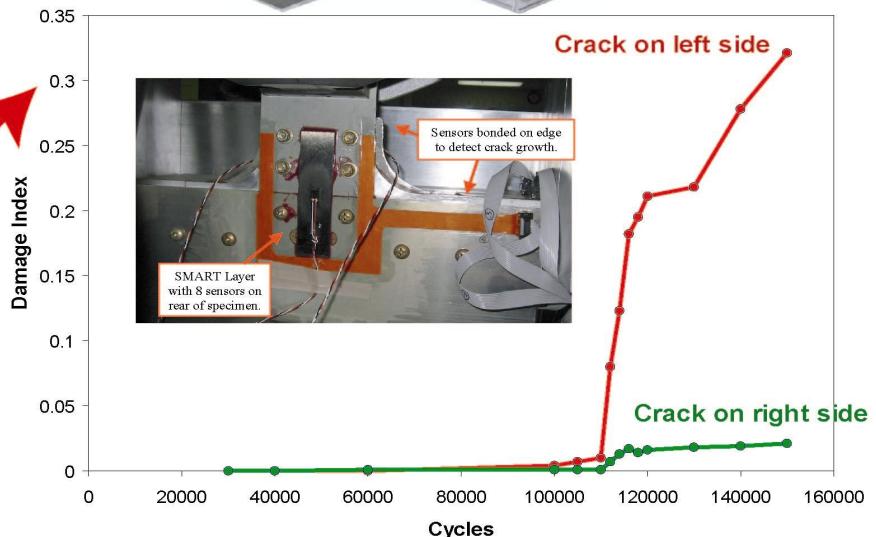


Load cycles





Test component



*** Bolted Joint Test Results ***					
Date	Time	Cycles	Measured Crack Length	Estimated Crack Length	Uncertainty
08/23/04	15:04:03	1000	0.158 in.	-----	-----
08/23/04	15:56:31	2000	0.325	-----	-----
08/23/04	16:42:52	3000	0.762	-----	-----
08/24/04	09:11:36	4000	0.912	-----	-----
08/24/04	09:42:07	5000	0.993	-----	-----
08/24/04	10:30:23	6000	-----	1.186 in.	±0.099 in.
08/24/04	11:01:55	7000	-----	1.435	±0.131
08/24/04	11:41:04	8000	-----	1.654	±0.188
08/24/04	13:16:22	9000	-----	1.998	±0.243
08/24/04	14:04:37	10000	-----	2.373	±0.329
08/24/04	14:26:01	11000	-----	2.835	±0.417

*** SHMR Component Test Results ***
Sensor System: SMART Layer
Specimen Configuration: Disbond Growth
Specimen Number: 1

Date	Time	Cycles	Measured Disbond Area	Estimated Disbond Area	Uncertainty
01/06/05	05:46:52	10500	0.125	-----	-----
01/06/05	05:57:46	11000	0.125	-----	-----
01/06/05	06:11:14	11500	0.188	-----	-----
01/06/05	06:48:26	12000	-----	0.255	±0.151
01/06/05	07:11:38	12500	-----	0.272	±0.170
01/06/05	07:28:12	13000	-----	0.438	±0.360
01/06/05	07:40:32	13500	-----	0.710	±0.672
01/06/05	07:55:10	13800	-----	2.154	±2.545

Measured disbond sizes

Calculated disbond sizes using sensor data

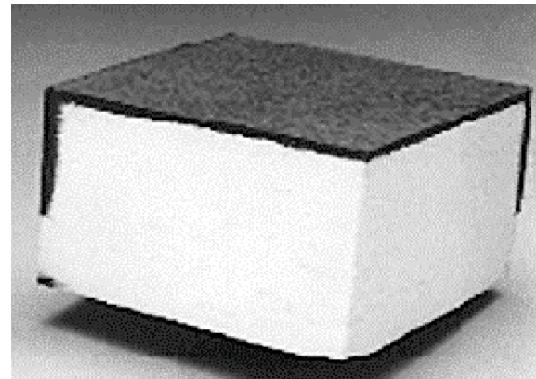
Bonded repair monitoring on F-16 component

Types of TPS

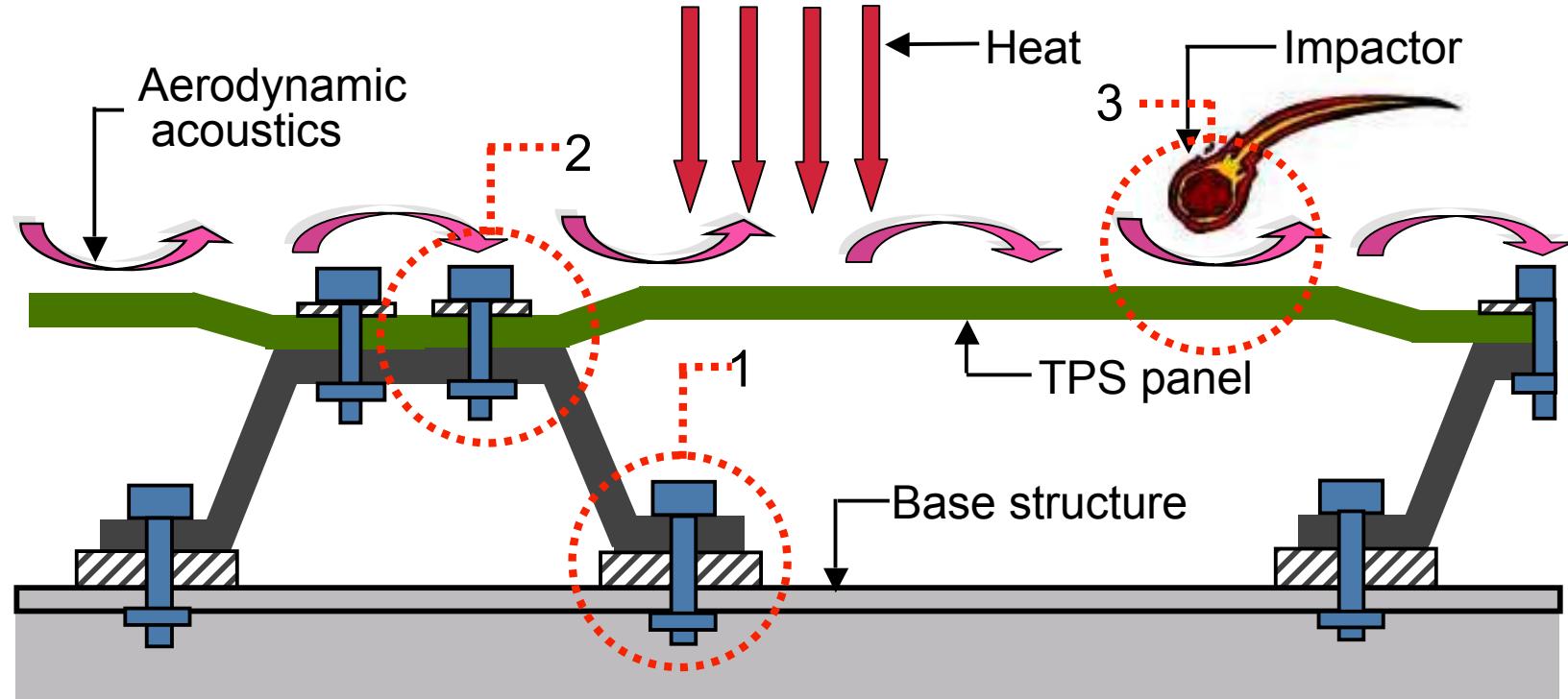
TPS panels :
Mechanically fastened joints



TPS tiles :
Adhesively bonded joints



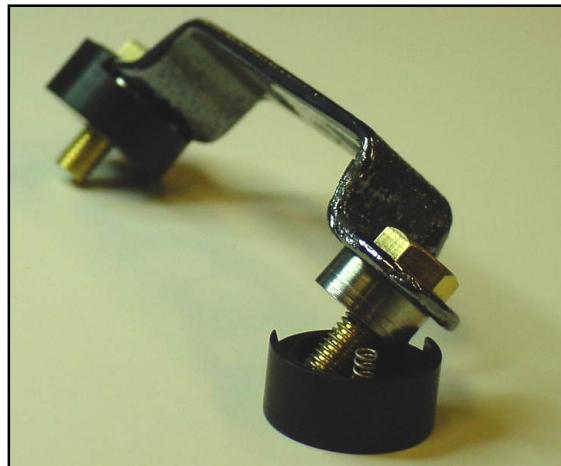
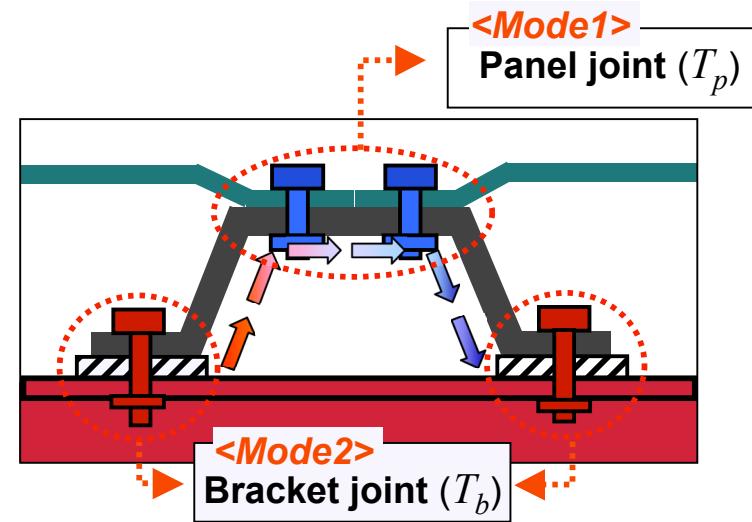
Bolted TPS



Bolted TPS with Built-in SHM

Attenuation-based Method

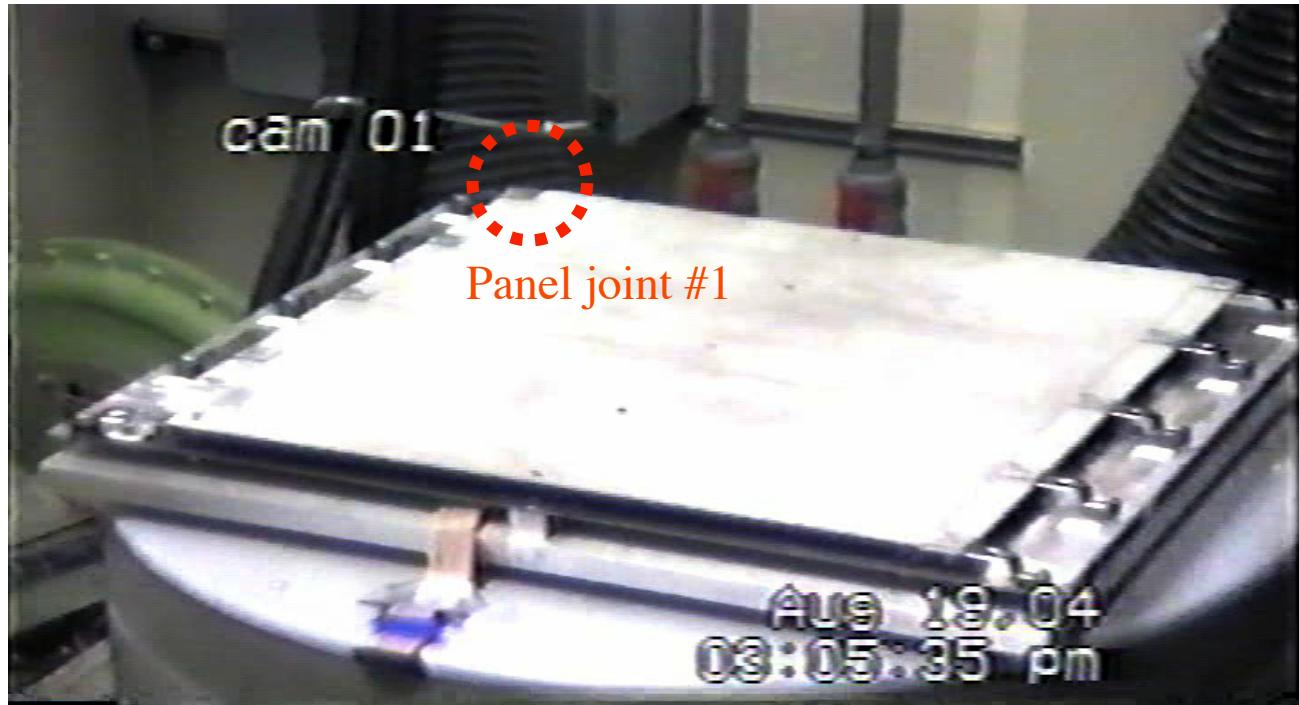
- Loosening location identification
- Torque level assessment



PZT-embedded Sensor Washer

- Sensitivity
- Survivability

Verification Tests - Shaker



Shaker tests at the Air Force Research Laboratory (AFRL) in Dayton, Ohio (Aug. 2004)

Test Condition

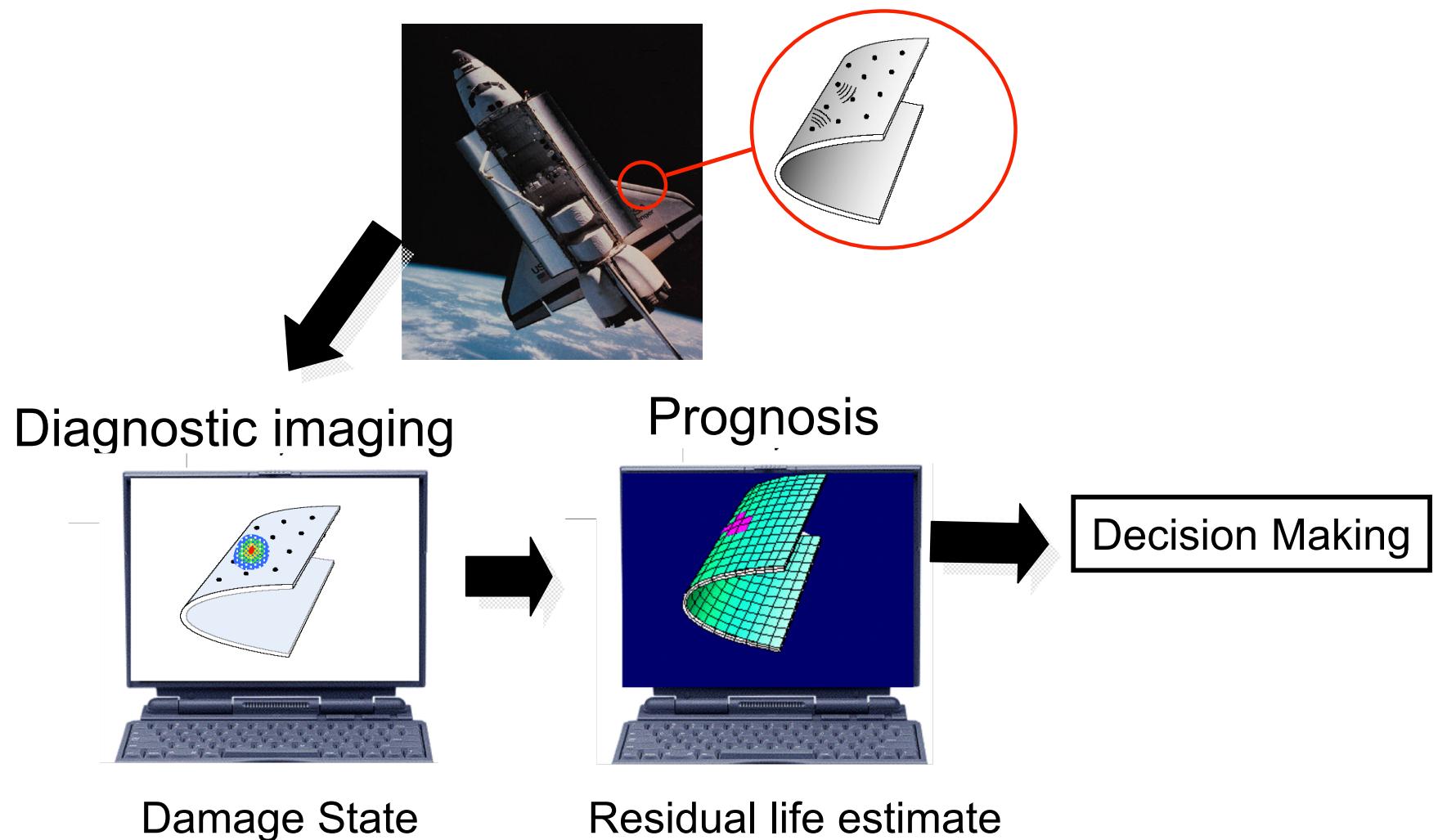
Noise level : 0.5 g ~ 7 g

Bandwidth : 50 ~ 500 Hz

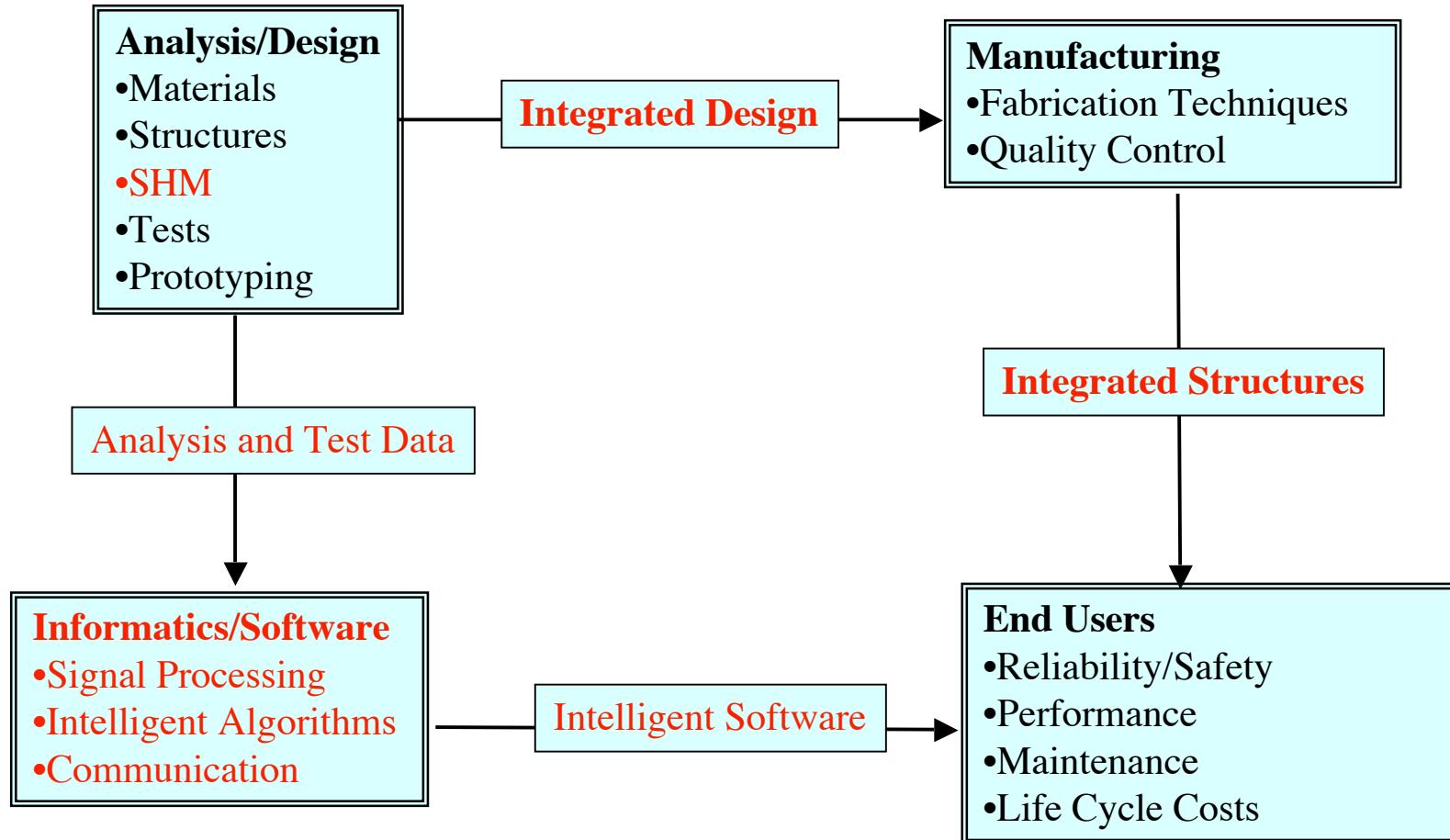
Duration : 10 minutes

Data acq. gap : every 2-minute

SHM-Embedded Design



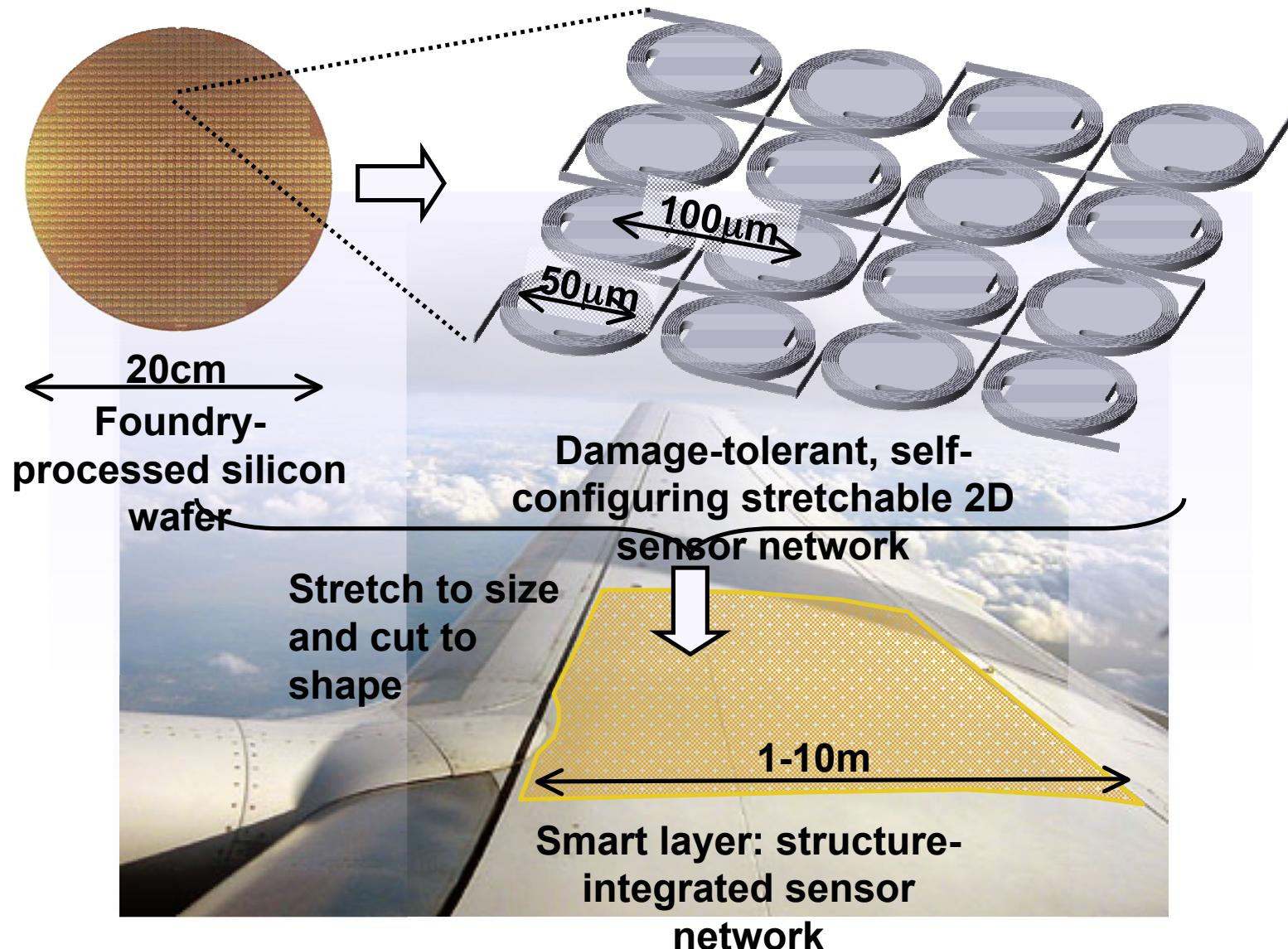
SHM-Embedded Structures



Challenging Issue: Scaling

- Actuators/Sensors:**
 - High performance, durable materials
- Sensor network:**
 - Damage tolerant, sizable, reconfigurable, durable.
- Hardware:**
 - Smart compact electronics (hardware/software integration)
- Software:**
 - Robustness, efficiency, data communication
- Integration:**
 - Interface compatibility, Durability, Self-diagnosis
- Optimization:**
 - New analytical and computational design tools

Damage-tolerant, stretchable, and reconfigurable silicon-based piezo- sensor network ?

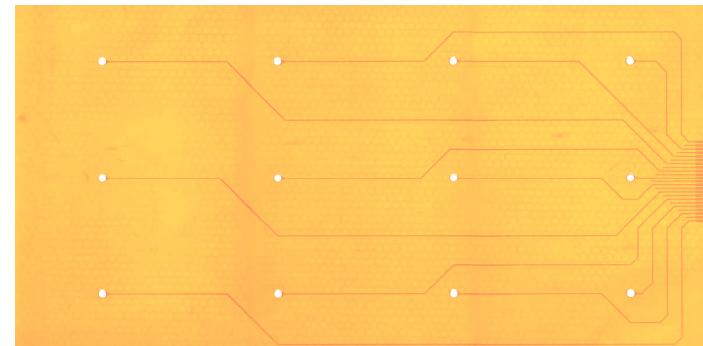


Slide provided by Prof. P. Peumans, Stanford University

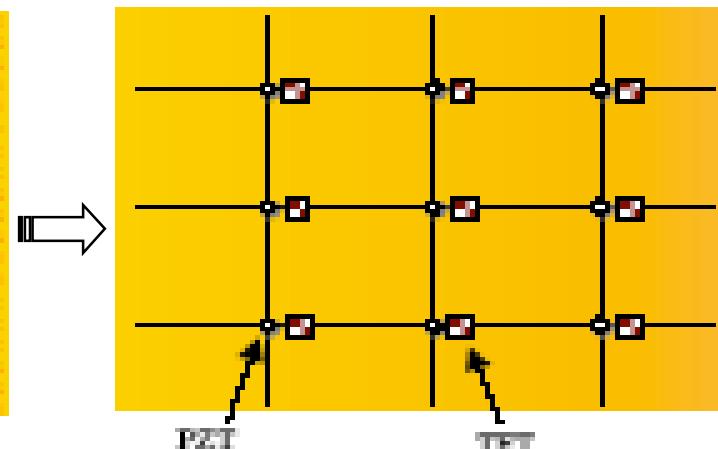
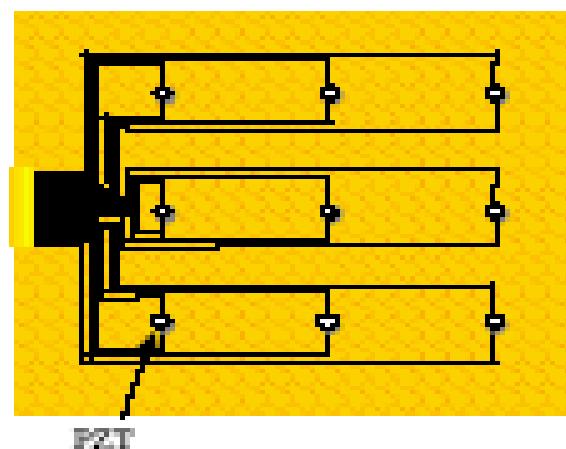
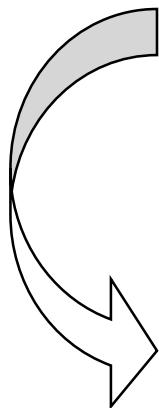
Embedded Control of Conformal Active/Passive SHM System?



Thin Film Transistor (TFT)



SMART Layer®



Slide provided by Acellent Technologies